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Valley glaciers persisted in the Lake District, north-west England, until ~16–15 ka as revealed by terrestrial cosmogenic nuclide (^{10}Be) dating: a response to Heinrich event 1?

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ABSTRACT: The Lake District of north-west England acted as an independent centre of ice dispersal within the more extensive British–Irish Ice Sheet (BIIS) during the Last Glacial Maximum, but relatively little is known about the pattern and timing of glacier retreat. Four new terrestrial cosmogenic nuclide (^{10}Be) surface exposure ages from boulders from a lateral moraine in the Duddon valley, south-west Lake District, have yielded internally consistent ages with uncertainty-weighted means of 16.51 ± 0.78 ka (using the Loch Lomond production rate with Lm scaling and 1 mm ka^{-1} erosion rate) and 16.15 ± 1.30 ka (using CRONUScalc with SA scaling and 1 mm ka^{-1} erosion rate). It is inferred that glacier retreat from the moraine occurred in the interval ~16.5–16.1 ka but that a valley glacier continued to exist, probably until ~15 ka. The Duddon valley ages agree with other surface exposure ages from Wasdale, Watendlath and the Shap fells, together demonstrating that glacier ice was still widespread in the Lake District at ~17–15 ka. There is also consistency with ages from other sectors of the BIIS that are considered to have responded to North Atlantic Heinrich event 1. Copyright © 2018 John Wiley & Sons, Ltd.

KEYWORDS: Heinrich event 1; Lake District; terrestrial cosmogenic nuclide surface exposure dating; valley glaciers.

Introduction

The NERC-funded BRITICE-CHRONO project (www.sheffield.ac.uk/geography/research/britice-chrono/home) is facilitating significant advances in our understanding of the style, pattern and rate of retreat of the last British–Irish Ice Sheet (BIIS). This systematic and directed campaign is concentrating largely on offshore areas (North Sea, Irish/Celtic Sea, Malin Sea, Atlantic shelf) but extends a short distance onshore adjacent to these marine sectors. Although terrestrial upland regions are not the focus of the BRITICE-CHRONO project, their deglaciation having received previous substantial attention (e.g. Ballantyne *et al.*, 2013; Ballantyne and Stone, 2015; Hall *et al.*, 2016; Hughes *et al.*, 2016), there are still some localities where more detailed research would enable closer temporal links to be forged with events documented and constrained in the marine/coastal transects of the project. This work would further inform about the later decay stages of the last ice sheet.

One such area is the Lake District of north-west England, a small upland massif of ~2500 km^2 with its highest point 978 m above sea level (asl). During the last glaciation (~30–15 ka) the Lake District functioned as an independent centre of ice dispersal within the more extensive BIIS (Fig. 1A). This is evidenced by the distribution of local erratics, the absence of allochthonous erratics, and the orientations of roches moutonnées, drumlins and striae (Wilson, 2010; Evans, 2015). Ice moving north from the Lake District ice dome met ice moving south from Scotland causing deflection of both ice masses to the east and west; Lake District ice also drained west and south to the Irish Sea and Morecambe Bay and became incorporated, in part, into the Irish Sea Ice Stream (ISIS); eastward ice movement was across the Eden Valley and northern Pennines (Evans *et al.*, 2009; Livingstone *et al.*, 2012). This ice dispersal pattern is known from the distribution of erratics derived from rocks of the Borrowdale Volcanic Group (BVG), mostly lavas and tuffs from the central Lake District, the metasedimentary Windermere Supergroup, mostly greywacke from the southern Lake District, the granite plutons at Skiddaw, Threlkeld, Shap, Eskdale and Ennerdale, and the various intrusive igneous rocks of the Carrock Fell Complex (Fig. 1B).

Although the Lake District bears many hallmarks of repeated glacial erosion and deposition (Wilson, 2010; Evans, 2015), it has proved particularly difficult to establish for how long the mountain glaciers persisted following withdrawal of the ISIS at ~26–24 ka from its maximum limits in the Celtic Sea, to a position at ~18–17 ka that is marked by the Bride moraine across the north of the Isle of Man and the Kirkham moraine in west Lancashire (Chiverrell *et al.*, 2013; Smedley *et al.*, 2017a, b; Fig. 1C). Coope and Pennington (1977) reported a basal ^{14}C age of 14 623 ± 360 years (17.8 ± 0.9 cal ka BP) from organic muds in Low Wray Bay, Windermere (Fig. 1B), and for some time this was the only age relating to deglaciation of the mountainous part of the area. This age has since been considered as anomalously old (Tipping, 1991; M. J. C. Walker, pers. comm. 2007; Wilson and Lord, 2014; Small *et al.*, 2017a) but it has continued to be regarded as a reliable indicator of ice-free conditions for this extensive south-draining catchment (Clark *et al.*, 2012a; Livingstone *et al.*, 2012; Pinson *et al.*, 2013; Chiverrell *et al.*, 2016).

At two other valley sites underlain by the BVG (Wasdale and Watendlath; Fig. 1B) single terrestrial cosmogenic nuclide (TCN) surface exposure ages imply that glaciers were still present at ~15.6–14.2 ka (McCarroll *et al.*, 2010; Wilson *et al.*, 2013b). Together these ages also suggest that the Windermere ^{14}C age is anomalously old. However, Wasdale opens to the south-west while the Watendlath valley opens to

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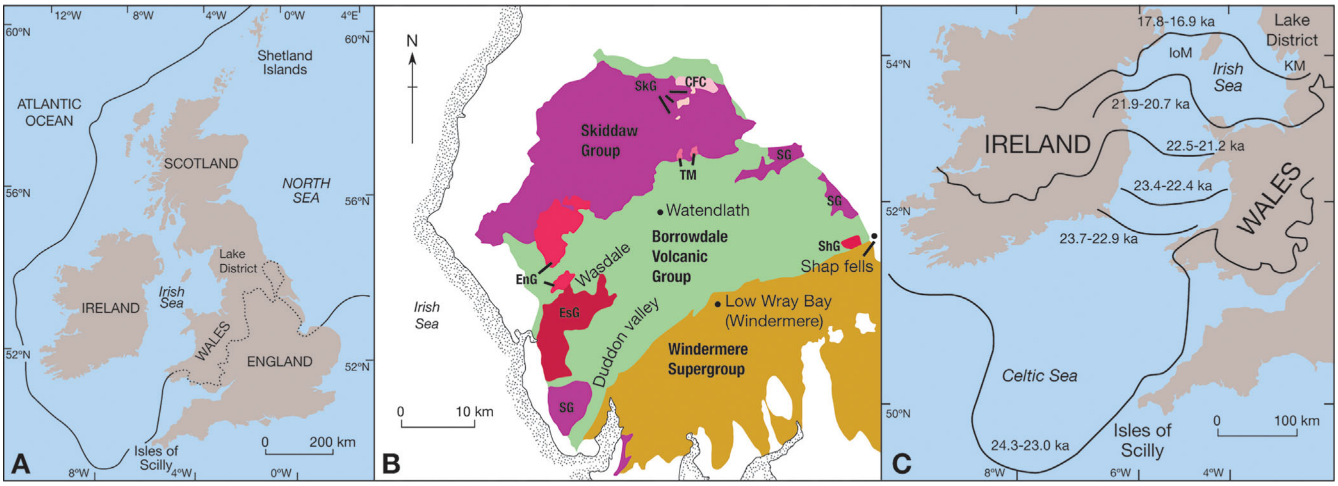

Figure 1. A: The Lake District in relation to the maximum extent of the British–Irish Ice Sheet during the Last Glacial Maximum. Ice limit after Scourse and Furze (2001), Clark *et al.* (2004), Sejrup *et al.* (2005), Bradwell *et al.* (2008), McCarroll *et al.* (2010) and Ó Cofaigh *et al.* (2012). B: Main rock types of the Lake District along with places mentioned in the text. SG: Skiddaw Group, CFC: Carrock Fell Complex, SkG: Skiddaw Granite, TM: Threlkeld Microgranite, ShG: Shap Granite, EnG: Ennerdale Granite, EsG: Eskdale Granite. Blank areas are post-Silurian rocks. C: Retreat stages of the last British–Irish Ice Sheet in the Irish Sea basin and on adjacent land areas (after Chiverrell *et al.*, 2013). IoM: Isle of Man: KM: Kirkham moraine.

the north, and valley aspect along with local climatic parameters cannot be ignored as factors influencing the rate of glacier retreat or glacier longevity.

Several TCN whole-rock ^{36}Cl analyses from both BVG bedrock and glacially transported boulders at various locations have yielded ages that pre-date the Last Glacial Maximum (LGM; ~27–23 ka), or are coincident with it (Ballantyne *et al.*, 2009; Wilson *et al.*, 2013b). These ages are considered compromised by inherited amounts of the nuclide because of limited glacial erosion during the LGM. Because individual site clusters of consistent TCN ages have not been obtained, constraining post-LGM glacier retreat in Lake District valleys remains a challenge.

The purpose of this paper is to report four TCN (^{10}Be) ages from quartz veins in boulders of BVG rock on a lateral moraine in the Duddon valley, south-west Lake District. The four ages are the first such cluster of ^{10}Be ages from a single valley moraine in the Lake District and their numerical/statistical consistency enables a robust timeframe for ice withdrawal from the moraine to be proposed. In addition, some of the previously published TCN (^{10}Be) ages from other Lake District locations have been recalculated and are discussed in relation to the results from the Duddon valley.

The Duddon valley and the lateral moraine

The Duddon valley (aka Dunnerdale) is a north–south draining glacial trough, opening into Morecambe Bay, in the south-west of the Lake District (Figs 1B and 2). In its upper reaches the valley is flanked by several summits rising to 700–800 m asl and in its lower reaches by summits of 300–600 m asl. Rocks of the BVG underlie the valley; for the most part these are andesitic, rhyolitic and dacitic lavas and tuffs with some volcaniclastic sandstones and breccias (British Geological Survey, 1998). Bedrock outcrops show evidence of intensive ice-scour, and numerous knolls and roches moutonnées characterize the valley sides and floor. Glacial drift is also common on the valley floor and lower hillslopes. In the headwater region moraine ridges and mounds attributed to a Younger Dryas Stade (YDS; 12.9–11.7 ka) glacier are present (Manley, 1959; Pennington, 1977; Sissons, 1980; Brown *et al.*, 2011).

There are very few prominent moraine ridges elsewhere in the Duddon valley but a particularly distinctive feature is situated on the lower slopes of the west-facing valley side in a mid-valley location close to Seathwaite (Fig. 2). It was described briefly by Mackintosh (1871) and Smith (1912), and a more detailed account along with associated glaciological and geochronological implications was provided by Wilson and Smith (2012), although no numerical ages were available. Because of this previous detail only a short summary of moraine characteristics and significance is given here.

The moraine extends in a broad arc for ~3 km from 320 to 120 m asl and is composed predominantly of large openwork boulders of BVG rocks (Figs 2 and 3). Maximum boulder length is 8 m and in places many boulders exceed 2 m in length. Within and adjacent to the moraine are several prominent roches moutonnées. A (sub-)lateral origin for the moraine was proposed by Wilson and Smith (2012) because both sub-angular and sub-rounded boulders are present, indicating they have undergone some abrasion most likely because of subglacial transport. Furthermore, direct supraglacial rockfall is unlikely to have provided the boulders because slopes immediately above the moraine are not steep or cliffed. A rockfall source for the boulders may have been farther up-valley, such as in the tributary basin containing Seathwaite Tarn. However, given the local dominance of roches moutonnées and ice-scoured terrain, the boulders are more likely to have been produced because of subglacial plucking. In a Lake District and wider British context the moraine is unique in terms of its size and composition.

Moraine age has not previously been established. Wilson and Smith (2012) considered the moraine was probably formed during a stillstand or readvance of the Duddon valley glacier during the general decay of the Lake District ice dome following the LGM. A YDS age is highly unlikely; pollen analytical evidence indicates that there was no glacier at Seathwaite Tarn during the YDS (Pennington, 1964, 1996) and the nearest moraines considered to date from the YDS are in a headwater valley ~7 km to the north (Manley, 1959; Pennington, 1977; Sissons, 1980; Brown *et al.*, 2011).

Sample collection and laboratory procedures

Quartz veins on the upper surfaces of four boulders were sampled for TCN (^{10}Be) dating using hammer and chisels (Figs 2 and 4). A compass and clinometer were used to record the geometry of the sampled surfaces, and the topographic shielding was determined using the CRONUS-Earth online

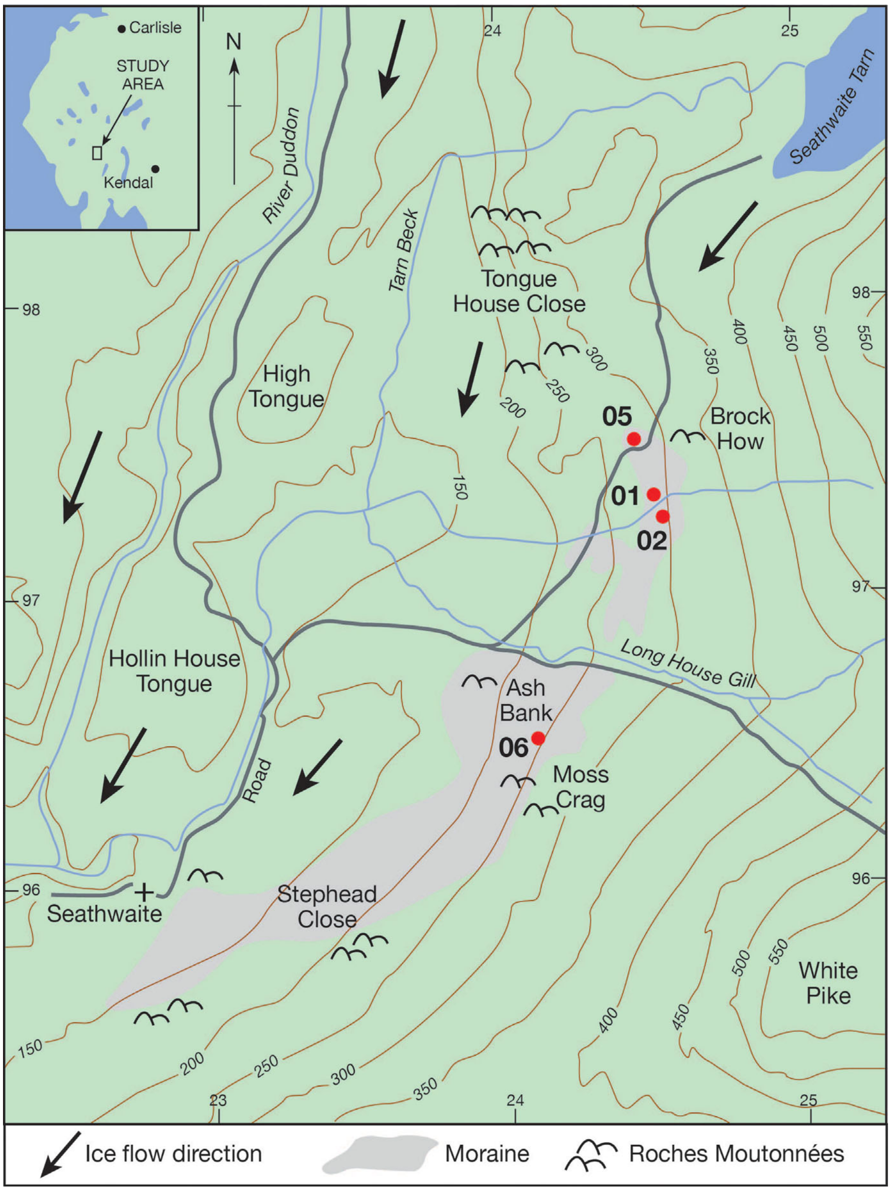

Figure 2. Configuration of the Duddon valley lateral moraine showing locations of boulders (01, 02, 05, 06) sampled for TCN dating. Contours are in metres and scale is given by the 1-km marginal grid. © Crown copyright Ordnance Survey, all rights reserved.

calculator (see below). Locations and altitudes were determined with a handheld GPS unit cross-referenced to a 1: 25 000 topographic map (Table 1).

All samples were crushed and sieved to 250–500 µm and preparation for ^{10}Be analysis followed the procedures described by Wilson *et al.* (2008), as modified by Glasser *et al.* (2009). The ^{10}Be accelerator mass spectrometry (AMS) measurement is described in detail by Xu *et al.* (2010). NIST SRM4325 with a ^{10}Be/^{9}Be ratio of 2.79×10^{-11} (Nishiizumi *et al.*, 2007) was used for normalization. This standard agrees with standards prepared by K. Nishiizumi, which were used as secondary standards. Cosmogenic concentrations include a blank correction of $4.5 \pm 0.3\%$. The standard uncertainties of the cosmogenic nuclide concentrations include the AMS counting statistics and scatter uncertainties from sample and blank measurements, which includes the long-term AMS and chemical preparation uncertainties.

Exposure Age Calculation and Results

The ^{10}Be surface exposure ages were calculated using the two methods adopted by the BRITICE-CHRONO project (Small *et al.*, 2017b). By this means the Duddon valley ages may be related directly to results deriving from that project.

First, ages were determined using version 2.3 of the online calculators formerly known as CRONUS-Earth ^{10}Be–^{26}Al exposure age calculators (http://hess.ess.washington.edu/math/al_be_v23/al_be_multiple_v23.php; Balco *et al.*, 2008) using the independently constrained Loch Lomond production rate (LLPR; 3.92 ± 0.18 atoms g^{-1} a^{-1}) (Fabel *et al.*, 2012). Production rates have not been determined for the Lake District but are unlikely to differ significantly from the LLPR given the relatively short distance (~230 km) between Loch Lomond (Scotland) and the Lake District. In version 2.3 of the age calculators a value of 4.0 ± 0.17 atoms g^{-1} a^{-1} is used for the LLPR rather than 3.92 ± 0.18 atoms g^{-1} a^{-1}, but the resulting differences in age are not significant. The LLPR was established from a geochronology provided by radiocarbon dating (MacLeod *et al.*, 2011). Exposure ages were based on the time-dependent Lm scaling (Lal, 1991; Stone, 2000) and assume 1 mm ka^{-1} of post-depositional surface erosion (cf. André, 2002; Nicholson, 2009; Larsen *et al.*, 2012).

Second, exposure ages were calculated using the CRONUScalc program v2.0 (Marrero *et al.*, 2016) using the default global production rate of 3.92 atoms g^{-1} a^{-1} for Sa scaling (Borchers *et al.*, 2016) and an erosion rate of 1 mm ka^{-1}. Both production rates agree within 1σ uncertainties with the range of production rates determined for other high-latitude

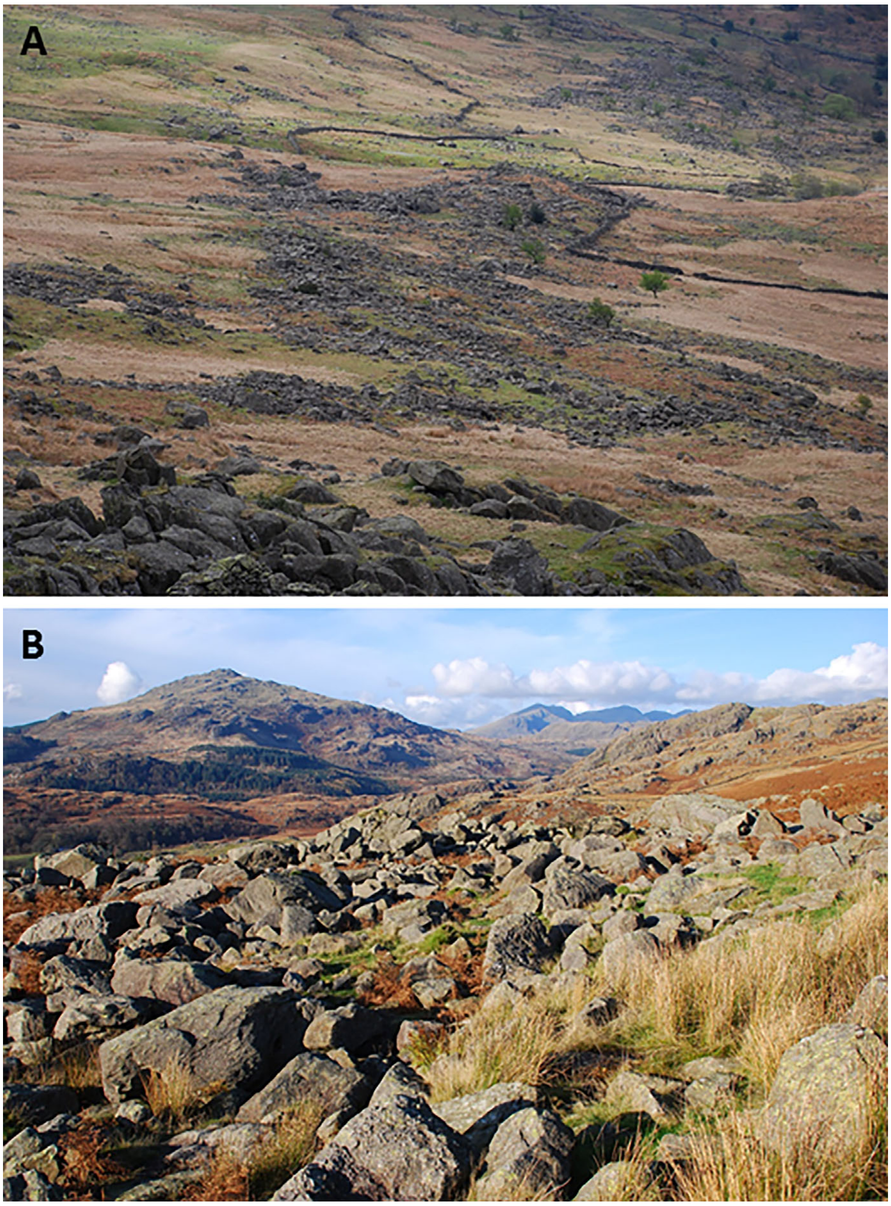

Figure 3. A: Downvalley view from the vicinity of Brock How of the upper part of the lateral boulder moraine. Some of the boulders in the Ash Bank area are visible at the upper right. B: Part of the boulder moraine near Brock How. Many of the boulders in this view exceed 1 m in length.

sites in the northern hemisphere (Phillips *et al.*, 2016; Small and Fabel, 2016). The cosmogenic (^{10}Be) data and exposure ages with uncertainties for each method of calculation applied are given in Table 2.

The four ages from the Duddon valley moraine range from 15.9 to 17.0 ka (LLPR), and from 15.5 to 16.6 ka (CRONUScalc). Irrespective of the method used the two ages calculated for each boulder are consistent within their 1σ analytical uncertainties (Table 2). However, determining which of the calculation methods, and their resulting ages, is the most reliable is not easy. In the following section ^{10}Be ages calculated using the LLPR are reported first with their external (total) uncertainties, CRONUScalc ages follow in parentheses.

Discussion

The four TCN ages from the Duddon valley moraine give reduced chi-square (χ^2_R) values of 0.71 (LLPR) and 0.84 (CRONUScalc). These are below the threshold value of 2.6 ($p < 0.05$, $n = 4$), and are taken to indicate an absence of anomalous values within the dataset (Bevington and Robinson, 2003). Therefore, the ages can be regarded as consistent with and representative of a single age population, with age scatter being due to measurement error alone (Balco, 2011; Applegate *et al.*, 2012; Ballantyne *et al.*, 2013; Small and Fabel, 2016). Consequently, the uncertainty-weighted mean of the four ages is 16.51 ± 0.78 ka (16.15 ± 1.3 ka) (Table 2; Fig. 5). These values provide best estimates for the timing of

Table 1. Details of samples for TCN dating from the Duddon valley moraine.

Sample code	Grid reference	Latitude (°N)	Longitude (°W)	Altitude (m OD)	Thickness (cm)	Density (g cm^{-3})	Topographic shielding
DUD-01	SD 24467 97287	54.36535	3.16265	280	1.5	2.65	0.9953
DUD-02	SD 24533 97261	54.35617	3.16165	290	0.5	2.65	0.9903
DUD-05	SD 24471 97512	54.36738	3.16264	280	1.0	2.65	0.9956
DUD-06	SD 24135 96531	54.35851	3.16756	245	6.0	2.65	0.9963

Figure 4. The four BVG boulders sampled for TCN dating. Boulder locations are indicated on Fig. 2. On DUD-01 and −05 the 1-m survey pole is aligned parallel to upstanding quartz veins; on −02 and −06 the boulders have been split parallel to the quartz veins which are disposed as thin sheets across the boulder surfaces.

moraine construction, and boulder exposure to cosmic radiation by glacier retreat ~16.5–16.1 ka. By inference, a substantial residual glacier ~7 km in length persisted in the valley.

For how long the Duddon valley retained its glacier after this time is not known with certainty. The Greenland ice-core chronology (Svensson *et al.*, 2006) indicates that a climate of severely cold conditions characterized the North Atlantic region between the LGM termination (~26–24 ka in the Celtic Sea) and the rapid warming that marked the beginning of the Lateglacial Interstade at 14.7 ka. A further ~500–1000 years may have elapsed before the Duddon glacier disappeared completely. Alternatively, glacier decay may have taken longer and continued into the early part of the Lateglacial Interstade, as suggested for parts of Scotland (cf. Ballantyne and Stone, 2012 Ballantyne *et al.*, 2013; Hall *et al.*, 2016).

Table 2. Cosmogenic (^{10}Be) data and surface exposure ages with total uncertainties at 1σ for the Duddon valley moraine samples, single samples from Wasdale and Watendlath, and two samples from Shap. Analytical uncertainties (1σ) are given in parentheses.

Sample code	AMS ID	^{10}Be (10^4 atoms g^{-1})	Exposure age* (LLPR)†	Exposure age‡ (CRONUScalc)
Duddon valley				
DUD-01	SUERCb10512	8.6956 ± 0.2716	16.54 ± 0.90 (0.53)	16.2 ± 1.4 (0.5)
DUD-02	SUERCb10513	8.8717 ± 0.2876	16.66 ± 0.92 (0.55)	16.4 ± 1.4 (0.5)
DUD-05	SUERCb10515	8.9758 ± 0.2926	17.00 ± 0.94 (0.57)	16.6 ± 1.4 (0.6)
DUD-06	SUERCb10516	7.8066 ± 0.2573	15.90 ± 0.88 (0.53)	15.5 ± 1.3 (0.5)
Mean§			***16.51 ± 0.78 (0.27)***	***16.15 ± 1.3 (0.26)***
Wasdale¶		7.3900 ± 0.2000	15.38 ± 0.80 (0.43)	15.1 ± 1.3 (0.4)
Watendlath	SUERCb1939	8.1350 ± 0.3470	15.45 ± 0.96 (0.67)	15.1 ± 1.4 (0.6)
Shap fells				
SHAP-02	SUERCb5608	8.7140 ± 0.3410	17.46 ± 1.04 (0.70)	17.0 ± 1.5 (0.7)
SHAP-07	SUERCb5611	8.8930 ± 0.3570	16.70 ± 1.00 (0.68)	16.3 ± 1.4 (0.7)
Mean§			***17.07 ± 0.90 (0.49)***	***16.65 ± 1.36 (0.49)***

* Exposure age based on the time-dependent Lm scaling (Lal, 1991; Stone, 2000) and assuming 1 mm ka^{-1} erosion.
† Loch Lomond production rate (Fabel *et al.*, 2012).
‡ Exposure age based on Sa scaling and assuming 1 mm ka^{-1} erosion. Note that CRONUScalc reports results to one decimal place.
§ Uncertainty-weighted mean value.
¶ ^{10}Be data from McCarroll *et al.* (2010). Normalized to the KNSTD ^{10}Be/^{9}Be standard.

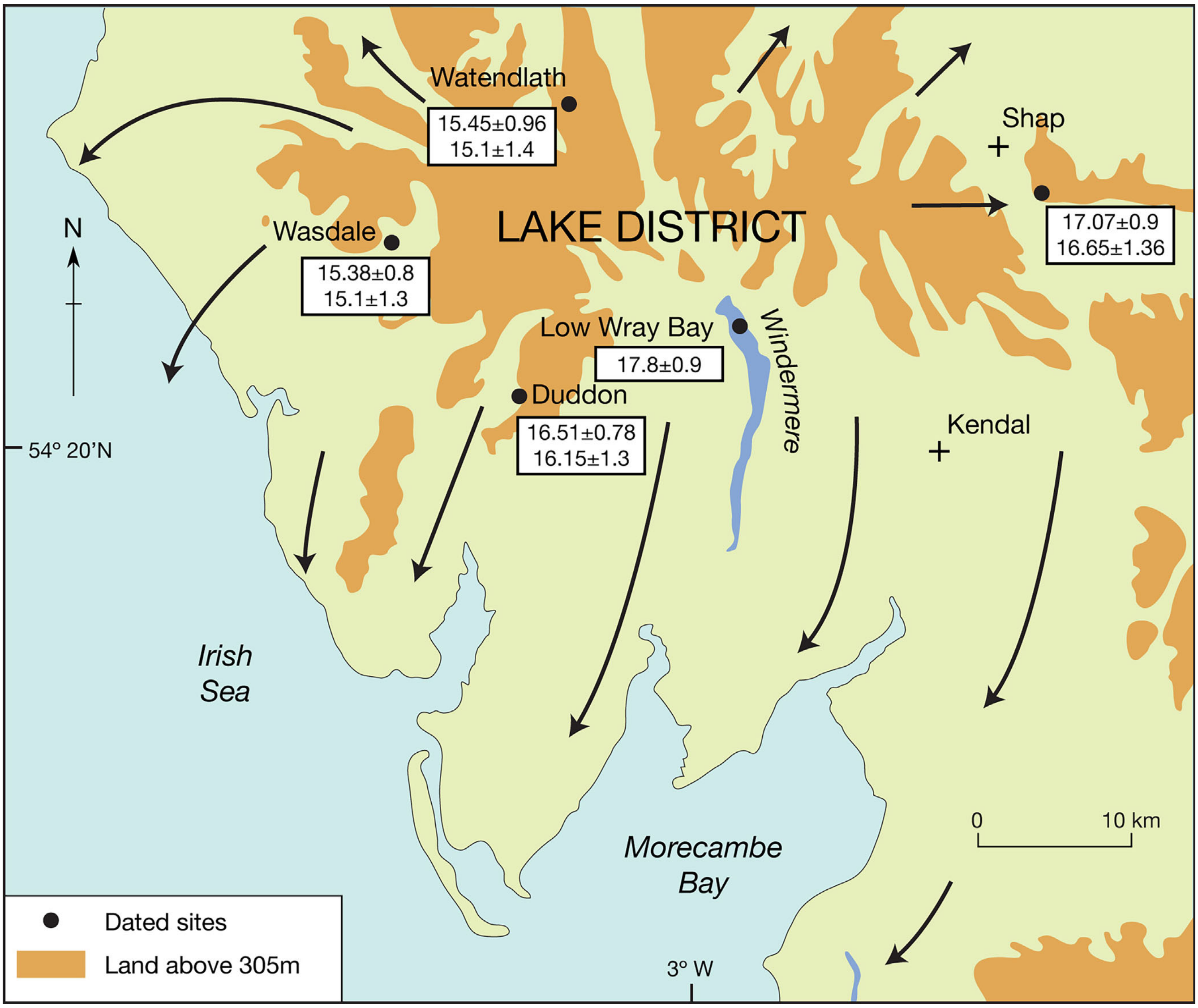

Figure 5. Locations of Lake District sites with TCN (^{10}Be) surface exposure ages. The first age in each box is that calculated using the LLPR, the second age is that calculated using CRONUScalc. The location of the Low Wray Bay, Windermere, ^{14}C age is also shown. Arrows indicate generalized directions of ice flow during the Last Glacial Maximum. For clarity Windermere is the only lake shown.

The existing TCN ages from Wasdale and Watendlath, discussed above, were also ^{10}Be ages from vein quartz from, respectively, the lee side of a roche moutonnée and the upper surface of an ice-transported boulder on the crest of a drumlin. Both samples were also from rocks of the BVG. The age for the Wasdale site was originally reported as 14.3 ± 1.7 ka using an assumed erosion rate of 1 mm ka^{-1} (McCarroll *et al.*, 2010); recalculation with the LLPR and CRONUScalc calibration data sets gives an age of 15.38 ± 0.8 ka (15.1 ± 1.3 ka). The age for the Watendlath boulder is

Table 3. Details of sites, materials and ages from within the limits of the last British–Irish Ice Sheet that may reflect a response to North Atlantic Heinrich event 1 (~17.5–16.7 ka).

Location	Materials dated	Dating method	Age (ka)	Associated event	Reference(s)
NE Ireland	*In situ* marine microfauna	^{14}C (cal)	~17.3–16.2	Killard point Readvance	Clark *et al.* (2012b), Ballantyne and Ó Cofaigh (2017)
W Ireland	Ice-transported boulders	TCN	~17.6–15.6	Killard Point Readvance	Clark *et al.* (2009), Ballantyne and Ó Cofaigh (2017)
Irish mountains	Ice-transported boulders	TCN	~17.1–15.9	Killard Point Readvance	Harrison *et al.* (2010), Ballantyne and Ó Cofaigh (2017)
Isle of Man	Glaciofluvial sediments	OSL	~17–14	Killard Point Readvance	Thrasher *et al.* (2009)
NE Scotland	Ice-transported boulders and bedrock	TCN	~16.3	Strath Spey Readvance	Hall *et al.* (2016)
E England	Glacigenic and glacio-lacustrine sediments	OSL	~16.8	North Sea/Withernsea Till Advance	Bateman *et al.* (2015, 2018)

15.45 ± 0.96 ka (15.1 ± 1.4 ka) (Table 2; Fig. 5). Greater confidence can be placed in the reliability of these (recalculated) single ages now that an age for the Duddon valley moraine is available. All these ages are consistent within 1σ external uncertainties and together indicate that glaciers in north- and south-draining valleys in the Lake District must have persisted until at least ∼16–15 ka.

Additional evidence for the late survival of valley glaciers in the Lake District comes from the Shap fells, on the eastern margin of the area (Figs 1B and 5), from where four TCN (^{10}Be) ages were reported from granite erratic boulders by Wilson *et al.* (2013a). Two of these (recalculated) ages are internally consistent with an uncertainty-weighted mean of 17.07 ± 0.90 ka (16.65 ± 1.36 ka) (Table 2), and are regarded as the best-estimate ages for deglaciation of that area. The broadly undulating Shap fells are ∼15 km east of the nearest Lake District glacial troughs and ∼30–40 km east of those of the central Lake District, including the Duddon valley. The glacier ice that transported and deposited the erratics moved east from the eastern valleys of the Lake District. This deglaciation age is consistent with the TCN ages reported above from valley sites and strengthens the argument for extensive glacier ice in the Lake District troughs at ∼17–16 ka, as depicted in the revised model of Livingstone *et al.* (2015). This, in turn, casts further doubt on the reliability of the basal ^{14}C age from Low Wray Bay, Windermere, which we consider should now be disregarded.

Wider significance of the Duddon valley ages

Although the Duddon TCN ages indicate the presence of a valley glacier at ∼16.5–16.1 ka, they provide no indication as to whether the moraine was created during a stillstand or a readvance of the glacier during the general decay of the Lake District ice dome following the LGM (Wilson and Smith, 2012). However, similar ages from glacially related landforms and sediments in other sectors of the BIIS have been used to infer that glacier stillstand or readvance was widespread around that time (Table 3).

In the north-east of Ireland, AMS ^{14}C ages from marine microfauna within *in situ* muds constrain a regional-scale readvance of ice (the Killard Point Readvance) in the northern Irish Sea Basin to ∼17.3–16.2 cal ka (Clark *et al.*, 2012b; Ballantyne and Ó Cofaigh, 2017). This readvance limit is marked by ridged and hummocky terrain made up of subglacial debris and outwash with interbedded marine muds deposited at a tidewater ice margin. A contemporaneous readvance of the ice sheet was reported to have occurred in western Ireland (Clark *et al.*, 2009), but although recalculation of the TCN ages by Ballantyne and Ó Cofaigh (2017) casts some doubt on this, a readvance cannot be entirely discounted. TCN ages from boulders on cirque moraines in the mountains of Ireland (range ∼17.1–15.9 ka: Harrison *et al.*, 2010; Ballantyne and Ó Cofaigh, 2017) agree within uncertainties with the age of the Killard Point Readvance and may indicate that cirque glaciers also underwent readvance at that time. Optically stimulated luminescence (OSL) ages of 17–14 ka from a sandur deposit in the Isle of Man are also consistent with a readvance (Thrasher *et al.*, 2009). In the Grampian Mountains, Scotland, TCN ages reported by Hall *et al.* (2016) indicate a readvance of the Strath Spey lobe of the BIIS $\sim 16-15$ ka. However, these ages were calculated using a production rate that, on average, yields ages that are ∼8% younger than those determined with the LLPR. Increasing these Grampian ages by 8% results in the mean value ($n = 8$) rising from 15.1 to 16.3 ka, an almost identical value to that determined for the Duddon moraine. OSL dating of glacigenic and glaciolacustrine sediments associated with the North Sea lobe of the BIIS indicates a readvance on to the Holderness coast of eastern England ∼16.8 ka and deposition of the Withernsea Till (Bateman *et al.*, 2015, 2018). The St. Bees moraine on the coast of the Lake District, although undated, has also been associated with the Killard Point Readvance by McCabe *et al.* (1998) and Merritt and Auton (2000).

Therefore, widespread evidence is available that indicates several sectors of the BIIS readvanced around ∼17–16 ka. This interval falls within Greenland Stadial 2.1a of the Greenland ice-core chronology (Rasmussen *et al.*, 2014) and overlaps with the North Atlantic ice-rafted debris event known as Heinrich event 1 (∼17.5–16.7 ka; Denton *et al.*, 2010; Stanford *et al.*, 2011). This event involved a massive discharge of icebergs from the collapsing Laurentide Ice Sheet that temporarily cooled the North Atlantic, interrupted a warming trend, significantly reduced Atlantic meridional overturning circulation, and initiated a ∼1-ka-long period of cold climate. As a consequence, ice sheet and glacier margins of the eastern North Atlantic seaboard experienced stillstand or readvance. The age of the Duddon valley moraine along with ages from Wasdale, Watendlath and Shap suggest that Lake District glaciers may also have responded to that event.

Conclusions

1. Four TCN (^{10}Be) surface exposure ages from vein quartz in boulders of the BVG have been obtained from a lateral moraine in the Duddon valley of the south-west Lake District. The ages range from 17.0 to 15.9 ka (16.6–15.5 ka), are internally consistent, and have uncertainty-weighted means of 16.51 ± 0.78 ka (16.15 ± 1.30 ka).
2. It is inferred that the moraine was constructed during overall glacier retreat ∼16.5–16.1 ka but that a substantial glacier survived in the valley, probably until at least ∼15 ka.
3. Support for the persistence of other valley glaciers in the Lake District in the period ∼16–15 ka is available from ^{10}Be ages for Wasdale, Watendlath and the Shap fells. Together with the mean age of the Duddon valley moraine, the ages indicate that the Lake District continued to host widespread glacier ice throughout the ∼17–15 ka interval.
4. The TCN ages are also consistent with ages from other sectors of the BIIS, together suggesting a regional response of the ice margin to Heinrich event 1.

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Abbreviations. AMS, accelerator mass spectrometry; BIIS, British–Irish Ice Sheet; ISIS, Irish Sea Ice Stream; LGM, Last Glacial Maximum; LLPR, Loch Lomond production rate; OSL, optically stimulated luminescence; TCN, terrestrial cosmogenic nuclide; YDS, Younger Dryas Stade.

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